DEVELOPMENT OF AN ENERGY ABSORBING COMPOSITE UTILITY POLE

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ABSTRACT

The serious hazard presented by unforgiving timber utility poles installed along our nation's roadways has long been recognized by the roadside safety community. However, relatively little attention has been devoted to the development of safer utility poles beyond breakaway timber pole designs. A new generation of utility pole designs employing energy absorbing composite materials offers a solution to developing and implementing safer utility poles that have a cost advantage over breakaway timber poles and can be tailored to achieve the desired functional performance and energy absorption characteristics inherently without the need for additional strength members or add-on energy absorption devices.

This research has resulted in the development of an energy absorbing fiberglass-reinforced composite (FRC) utility pole design that meets structural performance requirements for environmental loading in accordance with the National Electrical Safety Code (NESC) for Class 4 poles and safety performance criteria in compliance with NCHRP Report 350 Test Level 2 conditions for utility poles. Developmental testing and analyses were performed to support development of a prototype design for demonstration testing. Full-scale crash testing has demonstrated the ability of the composite pole to absorb vehicle impact energy by progressive crushing and fracture propagation as the vehicle is brought to a controlled stop. In addition to offering improved safety performance, the energy absorbing FRC pole provides significant functional advantages such as reduced weight, improved strength-to-weight ratio, increased longevity, ease of installation, low maintenance, and resistance to environmental degradation.

1.0 INTRODUCTION

Utility poles present a serious roadside hazard due to the large number of poles located in close proximity to the roadways and the unforgiving nature of existing pole designs. Vehicle collisions with utility poles result in nearly 10 percent of all fixed-object fatal crashes annually (1). In 1999, there were 1,070 fatalities and approximately 60,000 injuries related to utility pole crashes. Of the highway safety structures available to date, only one device, the Steel Reinforced Safety Pole (SRSP), has been designed specifically for utility poles (2). A new generation of utility pole designs employing energy absorbing composite materials will provide a solution to developing and implementing safer utility poles.

In addition to improved safety performance characteristics, an energy absorbing composite utility pole offers several inherent functional advantages over current timber poles including reduced weight, improved strength-to-weight ratio, ease of installation, low maintenance, and environmental friendliness, leading to increased potential for acceptance and implementation by the utility industry. These functional advantages were essentially the driving force behind the first generation of Fiberglass Reinforced Composite (FRC) utility poles manufactured by Shakespeare Company, Newberry, South Carolina, in 1993, and installed on a primary distribution system by the Montana Power Company (3). Since then, a wide variety of installations have been completed by small and large cities and municipalities, foreign government utilities, large investor-owned utilities and regional phone companies.

This paper presents the results of a Department of Transportation-sponsored Small Business Innovation Research (SBIR) project involving the development and performance demonstration of an energy absorbing fiberglass reinforced composite (FRC) utility pole design. The research included design development, finite element analysis, prototype manufacturing, developmental testing and full-scale crash testing in accordance with safety performance test and evaluation criteria identified in NCHRP Report 350 (4).

1.1 Background

The development of safer utility pole designs over the past two decades has focused on retrofitting existing wooden utility poles using breakaway features. The initial development of breakaway utility pole designs was performed at Southwest Research Institute (SwRI), beginning in 1973 with a study by Wolfe and Michie (5) in which various arrangements of holes, grooves and saw cuts were employed to weaken an existing wooden pole near the ground, enabling it to break away when struck by a vehicle. A bore hole, saw cut ceramic concept, RETROFIX, was recommended for further development due to its cost-effectiveness (6). However, this concept was not implemented primarily because the pole was significantly weakened in its capacity to withstand environmental loads. Further research efforts at SwRI and Texas Transportation Institute (TTI) were directed at the development of breakaway slip base devices which were adaptations of slip base technology previously developed for sign and luminaire supports (7). The original slip base retrofit concept was developed by Bronstad and used by Labra et. al. at SwRI (8). A slightly different design which combined a slip base lower connection with a progressively deforming upper hinge connection was later developed at TTI (9). This design, named the Hawkins Breakaway System (HBS), was developed to provide a more effective breakaway shear connection and overcome problems of pole detachment, conductor failure and entanglement, and the falling pole. The HBS design met the requirements of NCHRP Report 230 (10) and, by 1986, was implemented in several states, including Kentucky and Massachusetts. The HBS design was substantially modified for the installations in Massachusetts. This modified design is called the FHWA or Massachusetts design. Continued research at TTI led to an improved breakaway slip base design, AD-IV (11). This design, approved in 1993 by the FHWA for use on Federal-aid highway projects, employed a reduced number of bolts in the shear connection at the base, a square shape for the base plate, and a simplified upper hinge connection, resulting in reduced costs. Although limited field experience using Steel Reinforced Safety Poles has been positive, these devices have not gained wide acceptance by the utility industry. The approximate installation costs for the breakaway timber utility poles, as reported in a recent FHWA Status Report, “Breakaway Timber Utility Poles,” (12) ranged from $2,710 for an HBS retrofit design to $ 6,000 for an FHWA retrofit design.

Advances in composite structural design and fabrication methods provide an opportunity for developing FRC composite poles that are competitive in cost with breakaway timber poles and can be tailored to achieve the desired functional performance and energy absorption characteristics. Current composite manufacturing technology provides the ability to tailor the fiber reinforcement and introduce locally weakened zones at specific locations along the length of the pole during the manufacturing process in order to achieve the desired fracture behavior on impact without degrading the strength of the pole required for environmental loads.

2.0 DESIGN CRITERIA

General design criteria considered in the development and evaluation of the energy absorbing composite utility pole design included the following:

- the structural integrity of the pole to withstand environmental loads
- safety performance
- cost (including raw material, manufacturing, installation and maintenance)
- ease of implementation

The primary function of utility poles is to support service lines and transformers. Service loads include vertical loads from the weight of the cross arms, transformers and service lines and transverse forces due to unbalanced line tension, change in direction of lines and wind. The critical design condition in most cases is a directional moment at the base of the pole produced by wind on ice-coated lines. The class of pole and safety factor are specified by the National Electrical Safety Code (NESC). As an example, NESC requires that the rated strength of a wood pole be 4 times the computed total wind loading for that pole. This safety factor takes into account wood rot or decay and general inconsistency in wood pole properties. For the prototype design development, a Class 4 pole was selected to be representative of the most common class of poles. ANSI 05.1 Annex B establishes the strength requirements for utility poles in terms of the lateral load breaking strength. For a Class 4 pole, the strength requirement is 2,400 lbs. In evaluating the capability of candidate fiberglass reinforced composite utility pole concepts to withstand environmental loads, structural integrity was assessed by comparing the strengths with the values for timber poles of the same class.

The primary design goal established in coordination with DOT/FHWA at the outset of the program was to achieve progressive collapse of the composite pole upon impact by a small vehicle (820kg (1800 lb)) at speeds up to 70 km/hr (43 mph) while bringing the vehicle to a controlled stop. These impact conditions were established from the NCHRP Report 350 (4) test matrix (Test Level 2) for utility poles. Occupant risk criteria established in coordination with DOT/FHWA were in accordance with NCHRP Report 350 (4). The "preferred" limit for Occupant Impact Velocity (OIV) is 9 m/sec and the "maximum" OIV limit is 12 m/sec. The "preferred" and "maximum" limits for Occupant Ridedown Acceleration are 15 G's and 20 G's, respectively.

In establishing a target cost for candidate utility pole concepts, a cost range was determined based on data for breakaway timber poles (i.e., AD-IV, BTUP and Hawkins) as well as more recent guardrail and crash cushion designs. Based on this information, a target cost range of approximately $ 1,500 to $ 2,500 was established for the candidate design. Preliminary cost assessments were conducted to evaluate raw material and installation costs for an energy absorbing FRC utility pole compared to costs associated with breakaway timber pole designs. The results of this study indicated that the cost of an energy absorbing FRC utility pole would be substantially less than for the HBS, FHWA (Massachusetts) or AD-IV breakaway timber pole designs. The costs for the breakaway timber poles, including materials, labor and equipment, range from $2700 to $6000, compared to less than $2,200 for the energy absorbing FRC pole.

The safety performance improvements offered by energy absorbing FRC utility poles will never be realized unless such poles can be readily accepted and implemented by the utility industry. Therefore, implementation ease was considered as an important factor for candidate energy absorbing utility pole concepts. The goal was to achieve a design that was compatible with current installation procedures for timber poles (e.g., direct burial, standard hardware for cross-arms, etc.) with inherent reduction in required maintenance.

3.0 ENERGY ABSORBING COMPOSITE POLE DESIGN

The energy absorbing FRC utility pole design developed is a filament wound, fiberglass reinforced polyester composite pole. A filament wound construction was selected to combine economy of material use and flexibility of material placement suitable for long, tapered utility pole structures with varying cross-section geometry. The prototype pole design, shown in Figures 1 and 2, is 13.7 meters (45 feet) long and tapered from the base of the pole to the top of the pole. The pole is hollow with a tapered octagonal cross-section at the base of the pole transitioning to a tapered circular cross-section at the upper section of the pole. The octagonal cross-section provides locally weakened zones or "plastic hinges" at the corners to achieve energy absorption during impact via composite fracture initiation and propagation. The circular cross-section allows mounting cross arms to the top of the pole using conventional mounting hardware. The pole is fabricated using type E fiberglass and polyester thermosetting resin with a target glass/resin ratio of 65/35% by weight. The composite lay-up consists of helical layers which provide longitudinal strength/stiffness and hoop, or circumferential, plies for buckling resistance.

4.0 FINITE ELEMENT ANALYSES

Finite element analyses were performed for candidate design concepts and representative loading conditions to support the design development and evaluation effort. Structural analysis of candidate circular and octagonal pole designs subjected to environmental bending load was performed using the ANSYS FEA code (13). Simulations of the pendulum impact and full-scale crash test conditions were performed using LS-DYNA (14).

Material characterization tests, including longitudinal and transverse tension and compression testing of coupons as well as transverse compression testing of representative pole sections, were conducted in accordance with ASTM test methods to provide material property data for the FEA simulations. ANSYS FEA models of the octagonal pole design were developed for the environmental bending strength test simulation. The ANSYS FEA results provided useful information in evaluating different pole geometries, material thicknesses and fiber reinforcement orientations. Predicted deflections, failure stresses and failure locations agreed reasonably well with experimental results. The predicted failure load for the prototype octagonal pole design was 2775 lbs, which was within 3% and 8% of the two experimental failure loads for this design.

A significant objective of the subject research effort was to develop and validate an LS-DYNA model of the composite pole to support the design development and evaluation of crash test results. The model development effort provided a means for efficiently evaluating different pole design and impact test configurations. The LS-DYNA simulation effort was essentially carried out in three phases, as follows: (1) Simulation of Lateral Compression Tests, (2) Simulation of Pendulum Impact Tests, and (3) Full-Scale Crash Test Simulation. LS-DYNA Material Model 59 - Composite Failure (Plasticity Based), was used to model the composite poles. Preliminary models were developed for the compression test simulation to establish material properties and determine initial collapse forces for different circular and octagonal cross-section pole geometries. Having established material properties, models were generated to simulate pendulum impact test conditions involving a 820 kg (1800 lb) pendulum mass with a crushable honeycomb nose impacting the composite pole at 32 km/hr (20 miles per hour). The LS-DYNA simulation agreed fairly well with the pole impact response observed in the pendulum tests, but generally overpredicted the maximum deceleration level. These results were used to further improve the model for the full-scale crash test simulation. Refinements included updating material properties and improving the soil model. Results of this simulation agreed very well with the crash test results. Figure 3 presents a comparison of the LS-DYNA simulation vs. crash test results for a small car (820 kg Geo Metro) impacting the composite pole at 70 km/ hr. The impact angle was 15 degrees from the normal direction of traffic. Figure 4 presents a comparison of the predicted longitudinal acceleration history vs. experimental results. The LS-DYNA simulation results are nearly identical to the accelerometer data in this case.

5.0 DEVELOPMENT TESTS

Developmental testing, including lateral compression tests of short pole sections, bending strength tests and pendulum impact tests, were performed throughout the program to evaluate different pole geometries and composite lay-up configurations. Design configurations tested included circular and octagonal pole geometries with different composite lay-ups. Results of this testing demonstrated that an octagonal cross-section results in 30-40% lower collapse loads than circular poles of the same diameter.

Bending tests of different pole designs were performed at Shakespeare in accordance with ANSI C136.20 to evaluate load vs. deflection behavior and ultimate failure load. As shown in Figure 5, the pole is supported at the base below the ground line location using three straps. The load is applied at a location two feet from the tip of the pole. The different developmental pole design configurations were tested to failure loads ranging from 1150 lbs. to 2600 lbs. For poles that exhibited strengths above the 2400 lb load requirement, significant deflection (> 5 ft) was observed prior to failure.

Developmental testing also included pendulum impact tests conducted at Shakespeare to evaluate the impact response behavior and energy absorption characteristics of different FRC pole designs. All of the pendulum impact tests were conducted with a 820 kg (1800 lb.) reinforced concrete mass with a ten-stage crushable honeycomb nose impacting the pole at a velocity of approximately 34 km/hr (20 miles per hour) and a height of approximately 457 mm (18 inches) above grade. Wires were attached to cross-arms mounted on the test article pole and extended to two wood poles on either side of the test pole along the direction of impact. Acceleration time histories were recorded during the impact event. Figure 6 presents representative pendulum impact test results. As shown, the composite pole exhibited significant crushing and fracture propagation for this design.

6.0 DEMONSTRATION TESTING OF PROTOTYPE DESIGN

The results of the developmental testing and finite element analyses were used to develop a final prototype design concept for the energy absorbing composite pole. This design, previously described in Section 3, was subjected to environmental strength testing in accordance with industry standards (i.e., ANSI 136.20) and full-scale crash testing in accordance with NCHRP Report 350 recommended procedures for utility poles.

6.1 Environmental Bending Tests

Environmental testing of the final prototype design was performed at Shakespeare in accordance with ANSI 136.20, as described previously in Section 5 and illustrated in Figure 5. Two prototype poles were tested to failure. In both cases, failure occurred near the base of the pole corresponding to the ground line location. Loads recorded at failure were 2565 lbs and 2695 lbs, resulting in positive margins of safety of 0.07 and 0.12, respectively. These tests successfully demonstrated the structural integrity of the final prototype composite pole design for a Class 4 pole subjected to environmental bending loads.

6.2 Full-Scale Crash Tests

Two full scale crash tests of the final prototype design were performed at the Southwest Research Institute (SwRI) test facility located at Brooks Air Force Base in San Antonio, Texas. The purpose of these tests was to evaluate the safety performance of the final prototype octagonal composite pole design in accordance with NCHRP Report 350 Test Level 2 conditions for utility poles. Both tests involved a 820 kg Geo Metro impacting the pole at 15 degrees from the normal direction of traffic. Vehicle speeds were 50 km/hr (31 mph) and 70 km/hr (43 mph). Figure 7 shows the impact direction and location for both tests. In both tests, the front bumper and hood sustained considerable damage prior to the initiation of pole crushing and fracture propagation along the corners. The lower speed test resulted in visible fracture initiation of the composite material along the corners, as shown in Figure 8. In the higher speed test, more complete crushing and fracture propagation occurred until the vehicle was brought to a controlled stop, as seen in Figure 9. The pole remained upright after each test and the wires remained attached to the cross-arms. Figure 10 shows the post-test condition of the fractured pole for the higher speed test. Vehicle damage was confined to the front end, similar to the lower speed test. No windshield damage or occupant compartment intrusion occurred.

Occupant risk values obtained from the crash tests are summarized in Table 2. Both tests resulted in acceptable values for the occupant impact velocity and ridedown accelerations. For both tests, the longitudinal OIVs are below the "maximum" limit of 12 m/sec and the longitudinal ridedown accelerations are below the "preferred" limit of 15 G's specified in NCHRP Report 350 (4).

7.0 SUMMARY AND CONCLUSIONS

This research has resulted in the development of an energy absorbing composite utility pole that meets structural performance requirements for environmental loading in accordance with the National Electrical Safety Code (NESC) for Class 4 poles and safety performance criteria in compliance with NCHRP Report 350 Test Level 2 conditions for utility poles. Testing and analyses were performed to support development of a prototype design for demonstration testing. The energy absorbing FRC pole design is a filament wound, hollow composite pole with a tapered octagonal cross-section at the base of the pole that transitions to a circular cross-section at the top of the pole. Full-scale crash testing has demonstrated the ability of the pole to absorb vehicle impact energy by progressive crushing and fracture propagation as the vehicle is brought to a controlled stop. In addition to offering improved safety performance, the energy absorbing FRC pole provides significant functional advantages over conventional timber poles that should increase the potential for acceptance and implementation by the utility industry. These functional advantages include reduced weight, improved strength-to-weight ratio, increased longevity, ease of installation, low maintenance, and resistance to environmental degradation. The inherent strength and energy absorption characteristics of this FRC utility pole design also eliminate the need for additional strength members or add-on energy absorbing devices which contribute to increased installation and maintenance costs.

8.0 ACKNOWLEDGEMENTS

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TABLE 1. Comparison of Timber and Fiberglass Reinforced Composite Utility Poles (11).

	Fiberglass Composite	Timber
Weight (Class 4, 40 ft.)	475 lbs.	1000 lbs.
Longevity	80 yrs (minimum) Uniform performance	20-50 yrs Declining performance
Environmental	No chemical treatment	Chemical treatment
Maintenance	None	Every 5-7 yrs
Installation	Faster Fewer linemen required Easy access	Heavy equipment required Limited access
Strength (e.g., Class 4, 40 ft.)	2400 lbs. (Minimum)	2400 lbs. (Average)

TABLE 2. Full-Scale Crash Test Results for Energy Absorbing Composite Utility Pole.

Test Designation	Longitudinal Occupant Impact Velocity (m/s)	Lateral Occupant Impact Velocity (m/s)	Longitudinal Ridedown Acceleration (g's)	Lateral Ridedown Acceleration (g's)	Longitudinal Maximum 50ms Moving Average Acceleration (g's)
DET-CP-1 NCHRP TEST 2-80	10.6	1.0	-7.6	-2.3	-13.3
DET-CP-2 NCHRP TEST 2-81	10.8	1.1	-5.6	-0.9	-15.4

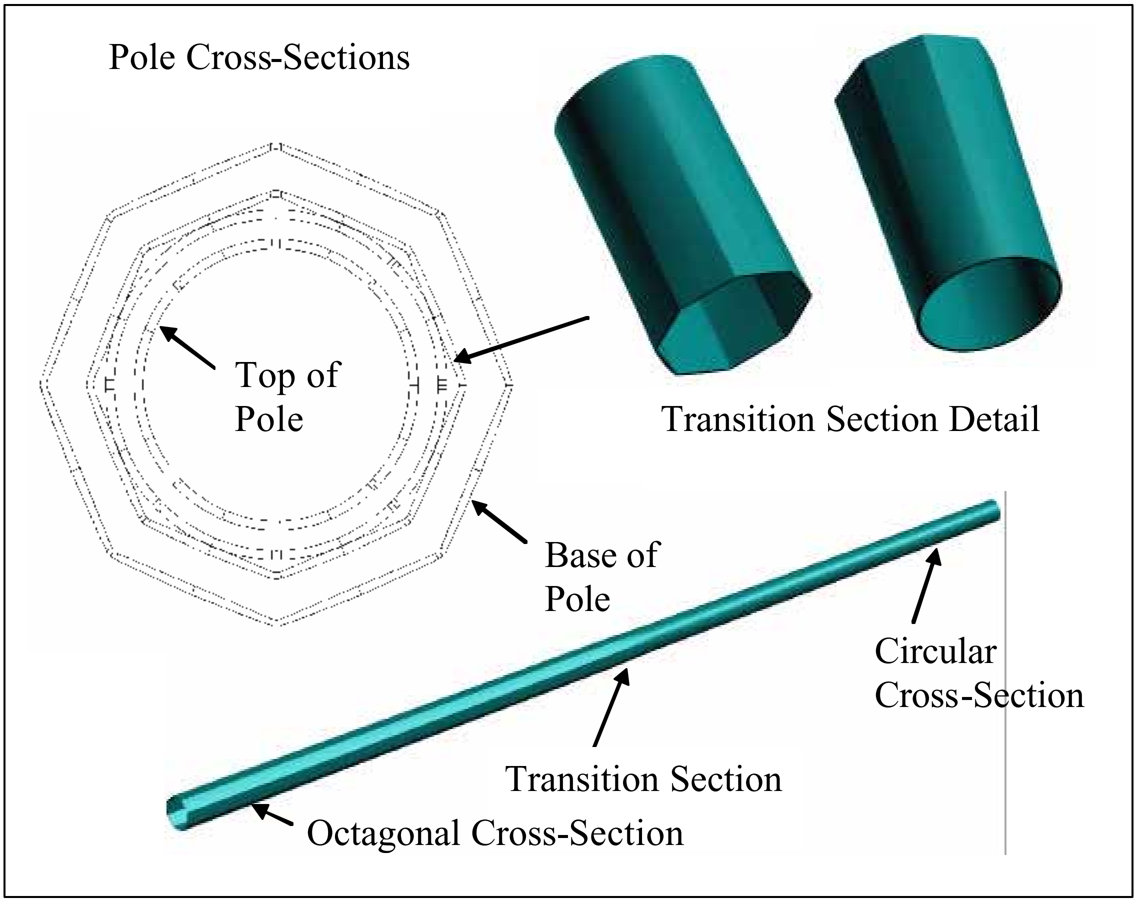
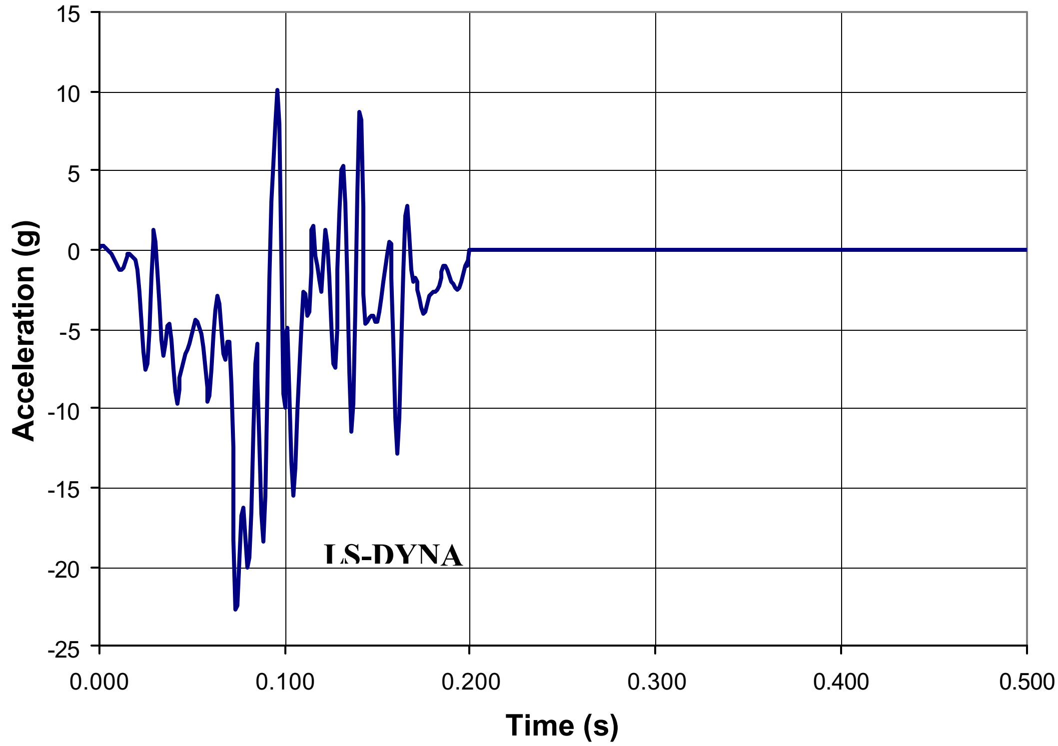


FIGURE 1. Energy Absorbing Composite Pole Design.

FIGURE 2. Prototype energy absorbing composite pole design installed prior to crash testing.

FIGURE 3. Comparison of LS-DYNA simulation and crash test results for 70 km/hr test.



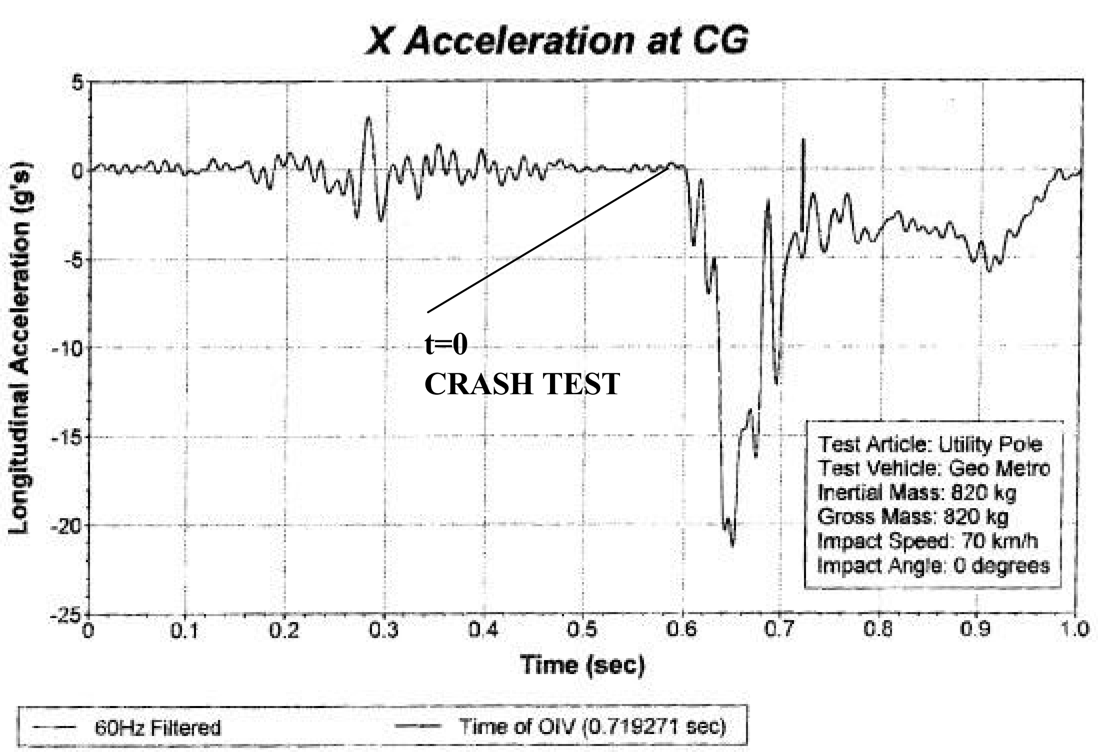


FIGURE 4. Comparison of LS-DYNA and experimental vehicle CG longitudinal acceleration histories for full-scale crash test.

FIGURE 5. Test configuration for environmental strength testing of composite utility poles.

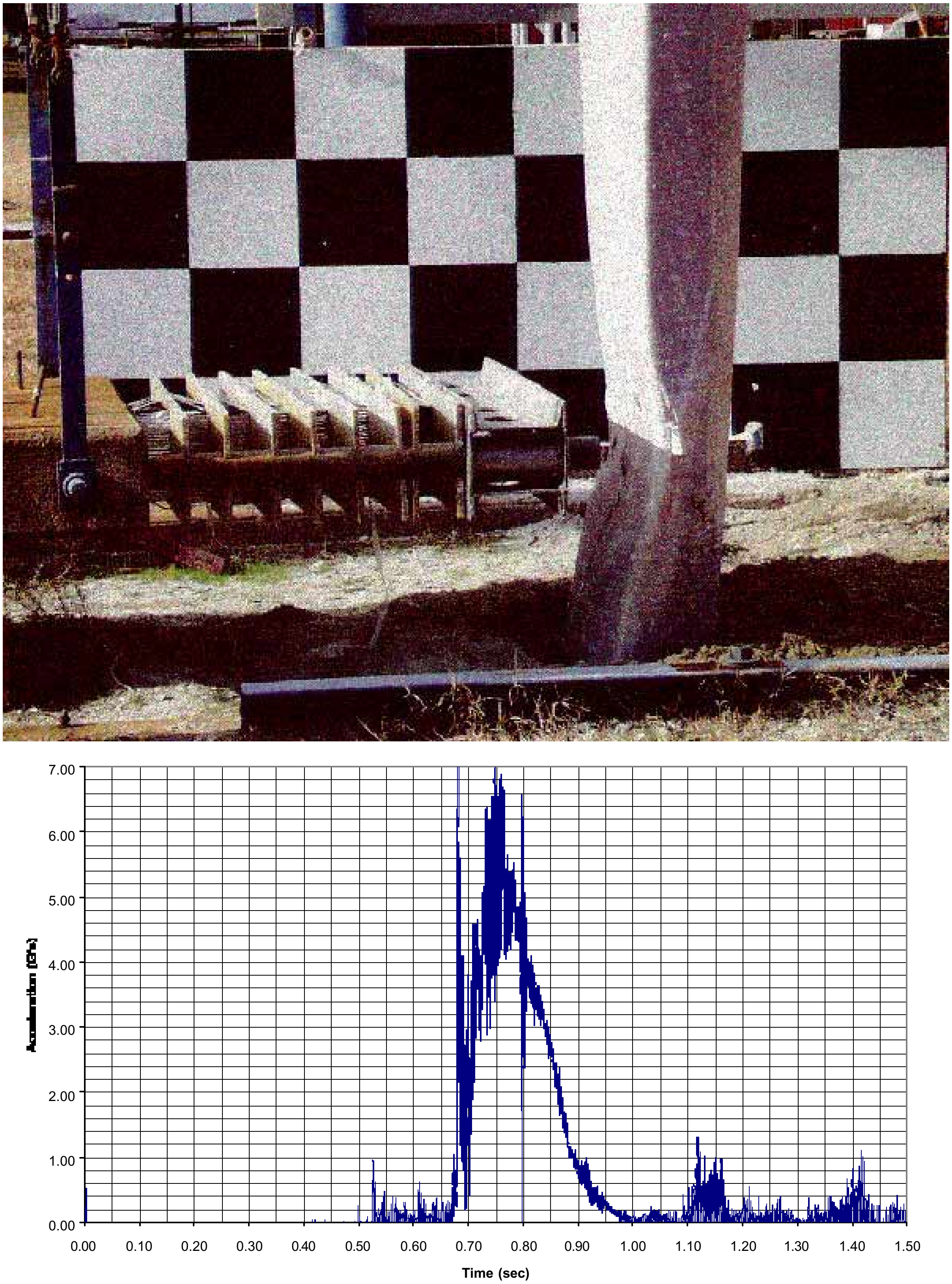


FIGURE 6. Pendulum impact testing of energy absorbing composite utility pole

FIGURE 7. Vehicle impact orientation and location for energy absorbing composite utility pole crash tests.

FIGURE 8. Post-test photograph of composite pole and vehicle following crash test at 50 km/hr.

FIGURE 9. Post-test photograph of composite pole and vehicle following crash test at 70 km/hr.

FIGURE 10. Post-test condition of fractured composite pole and vehicle damage following crash test at 70 km/hr.